EUV Source Collector

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ABSTRACT

A collector subsystem has been designed, built, and tested. The subsystem consists of a 320mm diameter ellipsoidal collector coated with a graded multilayer, mounting mechanics, thermal management capability, and a collector protection system. The EUV light emission can be collected with a solid angle of 1.6 sr. Collector substrates have been developed with the goal of offering both optical surface quality to support high multilayer mirror (MLM) reflectivity and material compatibility for long-term operation in the EUV source system. An interface-engineered MLM coating capable of maintaining high normal-incidence peak reflectivity at 13.5 nm during continuous operation at 400 °C has been developed. The thermal management of the system has been engineered and tested to maintain uniform substrate temperature during operation. Lastly, protection techniques have been developed to provide the collector with a long operational lifetime. Performance data for the entire subsystem are presented. The collector was installed in the source chamber of a laser-produced-plasma EUV source during system integration experiments using a tin droplet target. First results of the collected EUV output at the intermediate focus measured with a power meter and a fluorescence-converter-based imaging system are discussed.

Keywords: EUV collector mirror, EUV lithography, EUV light source, laser-produced plasma, multilayer mirror, EUV radiation power, collector lifetime

1. INTRODUCTION

EUV light sources generally emit radiation from the generated micro-plasma into all directions. Therefore, it is highly desirable to collect the emitted radiation power as efficiently as possible and redirect it towards the entrance of the illumination system of the lithography exposure tool. In order to keep the size of the mirror within reasonable limits the collector has to be mounted relatively close to the light emission region and thus needs to be protected from debris ejected from the plasma region to insure a sufficiently long mirror lifetime. Consequently, the optical collector is regarded as one of the most critical subsystems for extreme-ultra-violet (EUV) source systems. Since the optical requirements are quite challenging and since the manufacturing process consists of many steps it is a time-consuming process to develop and test a large advanced collector subsystem. For a prototype it is required to prove the full functionality of the entire light source system that includes delivery of EUV radiation to the intermediate focus (IF) position via the collector. In addition to the technical aspects it must also be demonstrated that the manufacturing is economically viable. In summary, the general requirements are that the collector subsystem needs to have high collection efficiency for EUV radiation, high resistance to debris generated by the plasma, have a long lifetime, a reasonable cost, and be exchangeable with consideration of semiconductor industry maintenance standards.

For integration with Cymer's laser-produced plasma (LPP) light source that is currently being developed [1, 2] we have designed, installed, and tested a near normal-incidence sub-aperture collector mirror with 1.6 sr collection solid angle. The mirror is intended for use during continuous operation at temperatures of up to at least 400 °C in conjunction with an LPP using liquid metal droplet targets containing lithium (Li) or tin (Sn) [3]. In this paper we discuss the various aspects of the entire collection subsystem, geometry and opto-mechanical design, and we describe heating tests of the mirror shell as well as lifetime tests on witness samples. We also present data characterizing the mirror substrate and the

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high-temperature multilayer mirror (MLM) coating and report first EUV data obtained with a XeF excimer-laser-produced Sn droplet source at the IF after mirror installation and alignment.

2. DESIGN CONSIDERATIONS, ADVANTAGES AND REQUIREMENTS

A favorable geometric configuration for light collection has the shape of a prolate ellipsoid since the radiation from the micro-plasma at the primary focus can then be refocused at the IF position (secondary focus point) that forms the interface between the source and the illuminator of the exposure tool. For an LPP EUV source a collection geometry with light reflection at near normal incidence is an attractive configuration, in particular, since a very large solid angle for collection can be accommodated due to the small etendue of the source. A MLM coating is then required to yield a high EUV reflectivity of the mirror. An advantage of the normal-incidence MLM design is that partial spectral purity filtering already occurs at the collector due to the narrow bandwidth of the coating leading to absorption of a large portion of unwanted EUV out-of-band radiation by the mirror without transfer to the IF. The laser beam can be focused through a central opening in the collector shell that does not consume a large collection area. In contrast to the nested shells of grazing-incidence mirrors generally employed for gas discharge sources, a single-shell unit can be readily designed for an LPP source avoiding all subunit alignment needs. Apart from its mechanical simplicity a monolithic design represents also a considerable cost advantage compared to a multiple-panel collection configuration with multiple alignment mechanisms of the kind that was employed on the Engineering Test Stand [4, 5]. Since the space behind the mirror is fully available a thick shell with large thermal mass, very low deformation potential and stress-free mounting can be designed. The space between the LPP and the mirror surface, on the other hand, can be used for suitable debris mitigation and protection schemes.

Thermal control can be applied via the backside of the collector to insure a uniform temperature distribution during operation. This is advantageous since it supports the previously presented technique to evaporate Li debris from the surface of the collector [1]. The performance of a high-temperature compatible MLM coating is discussed below in Section 6. A temperature in the range of 350 ºC – 400 ºC is needed to have conditions where the evaporation rate of Li exceeds the influx rate substantially. Due to the large thermal mass and high-temperature stable MLM coating our design provides the capability to absorb and retain radiated heat from the plasma without the need of elaborate cooling schemes as required in the case of grazing-incidence collectors thus eliminating the issue of thermal loading. By means of a heat exchanger mounted behind the collector substantial radiative heating or cooling can be applied as needed to maintain a constant and even temperature independent of plasma operation. Optical modeling of the entire configuration was also carried out. It has shown the potential for highly stable thermal and optical properties leading to low aberrations at its image point, the intermediate focus.

3. COLLECTION GEOMETRY AND OPTICAL DESIGN

As described in the previous section a single-shell ellipsoidal collector was chosen as the preferred geometric configuration. The optimal parameters for the elliptical cross section of the collector were determined by accommodating several geometric constraints in the optical design. For efficient light collection a solid angle of 5 sr was chosen for the final configuration. Matching of the acceptance cone of the illuminator at the IF position is required, as well as a reasonable size diameter (D) and focal distance (f). The resulting configuration is illustrated schematically in figure 1. Instead of employing a full-aperture mirror shell with 600 mm diameter we have opted to first build a sub-aperture configuration with half the diameter but the same elliptical cross section for our initial testing and system integration. This resulted in a light collection cone of 1.6 sr, as indicated in figure 1. The distance l between the LPP and the IF exceeds 1 meter for the configuration implemented. Detailed optical modeling of the image magnification and the aberrations occurring at the IF was carried out as a function of plasma diameter using a ray tracing program. Coma was determined to be the dominating aberration; however, the normalized encircled energy was found to be constant when the source size was varied for source diameters below 0.5 mm. The modeling gave also valuable input for image intensity distributions under imperfect mirror alignment conditions that lead to asymmetric distortions and shifts of the radiation distribution at the IF.

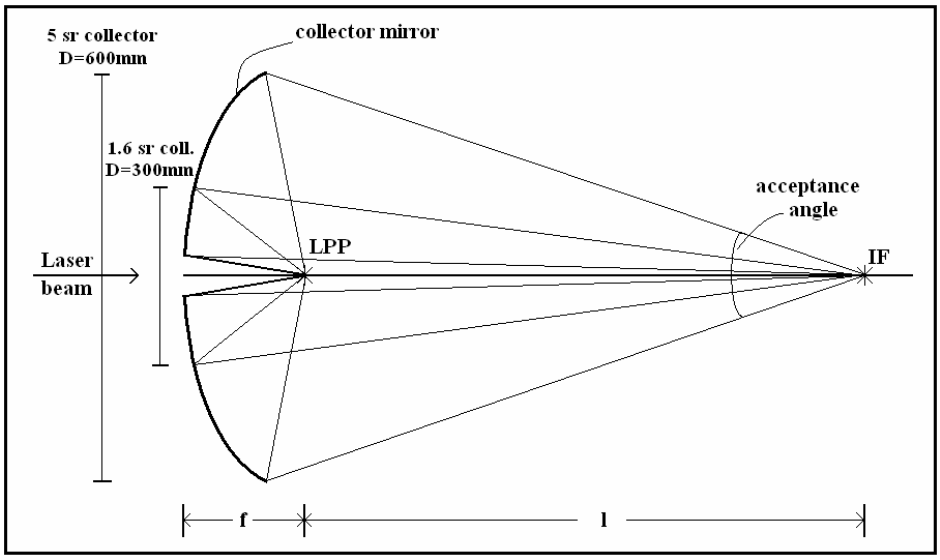


Figure 1: Light collection configuration with ellipsoidal mirror for refocusing the EUV radiation from the LPP to the IF. A 5 sr collector and a 1.6 sr sub-aperture configuration are shown schematically in comparison.

4. OPTOMECHANICAL DESIGN, COLLECTOR HEATING AND THERMAL MANAGEMENT

The collector is mounted on a large-diameter flange of the source chamber with the optical axis oriented horizontally. As shown in figure 2, a support structure holds a heat exchanger and the mirror shell. The purpose of the heater and heat exchanger is to maintain a constant mirror surface temperature at up to 500 ºC. The mirror can be heated during conditioning phases and during LPP operation at low repetition rates. In addition, the heat exchanger can be cooled during runs at high repetition rates in order to balance the radiative heat load from the plasma. Thermal sensors are attached at the mirror backside to generate the input signals for temperature control. The central opening is introduced to provide space for the laser beam focusing. Several different heating methods and configurations were considered and evaluated Efficiency and cost considerations lead to the selection of a radiative heating scheme for the mirror backside by means of two loops of resistively heated molybdenum wire on isolation posts. The heaters are located about 30 mm behind the mirror. The goal is to facilitate uniform thermal control at constant temperature during operation in the range of 300ºC – 500ºC. Conservative estimates of the heat load during operation at high repetition rates based on a one-dimensional radiation transfer model indicate that the heat removal can be readily managed when the mirror surface is held to these temperatures. Heater power and heat removal capabilities are in the range of 1.5 – 4.0 kW.

In order to minimize the movement and surface distortion of the mirror and to provide structural isolation from mechanical and thermal loading deformations, several different mechanical mounting schemes were investigated. The collector surface response was studied under thermal load using a discrete structural model. Based upon this analysis, a predominantly stress-free mounting of the mirror shell is accomplished by three mounting fixtures located at the mirror circumference, spaced apart by angles of 120º. The droplet stream and the laser focus are aligned and positioned at the primary focus of the mirror for optimal EUV collection.

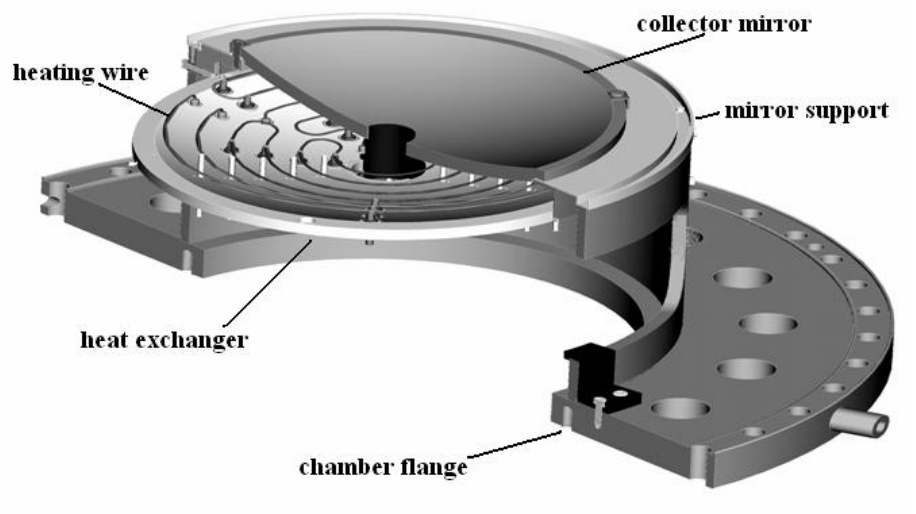


Figure 2: Cutout showing mirror mounting and heating arrangement

5. SUBSTRATE MATERIAL SELECTION AND PREPARATION, SURFACE ROUGHNESS

A suite of candidate materials was reviewed for use as mirror substrate. Silicon carbide was chosen as the substrate material due to its superior mechanical and thermal properties as well as its polishability and compatibility with the MLM coating and the target material. SiC is attractive in terms of mechanical stiffness and stability as well as low mass and low distortion. It is also characterized by a low coefficient of thermal expansion, a low specific heat and high thermal conductivity and emissivity. These features result in favorable properties of the mirror shell for thermal management and radiative heating and cooling. Large-size shells of polycrystalline material with small grain size can be produced in high-temperature growth reactors. A chemical-vapor-composites process leads to relatively fast and efficient deposition of the shell with near-net shape using SiC seed particles. Only minor post-process machining is required prior to the optical grinding and polishing.

SiC reflectors have previously been used for various applications at extreme and vacuum ultraviolet wavelengths demonstrating that substrate figuring and polishing to an Angstrom-range roughness is possible. Grind and polish procedures for the aspherical shape of the sub-aperture collector substrate were developed by the polisher yielding excellent uniformity data across the range of optical surface (70 mm – 300 mm radius). Several mirror shells were fabricated. After the polishing, the mid- and high-spatial frequency roughness was investigated with an optical measurement system. Figure 3 shows the small-field micro-roughness results obtained for a 200 μm x 100 μm region on one substrate yielding ~ 0.3 nm root-mean-square (rms) roughness. Additional investigations were carried out with atomic force microscopy (AFM) for several selected regions on the surface. Typical results obtained before and after MLM coating for regions of 10 μm x 10 μm are displayed in figure 4. Generally, AFM data indicated high-spatial frequency roughness numbers that were about a factor of 2 higher than those optically determined (~ 0.6 nm rms). However, no substantial change was observed in the AFM roughness data after MLM coating and heating to temperatures of 400 °C.

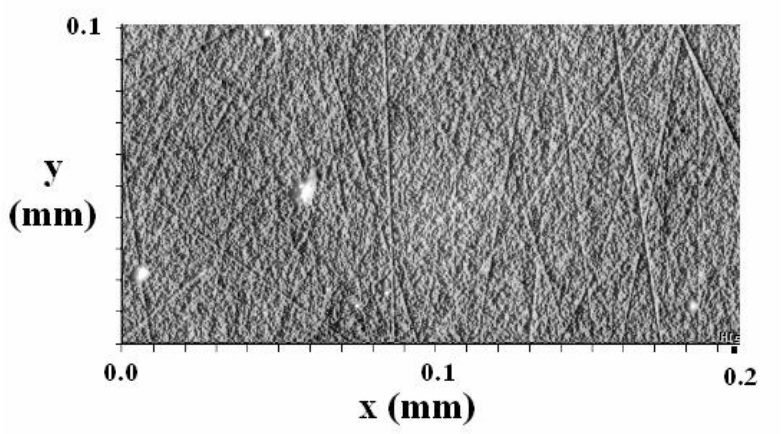


Figure 3: Optically measured small-field micro-roughness, typical average value of 0.3 nm rms.

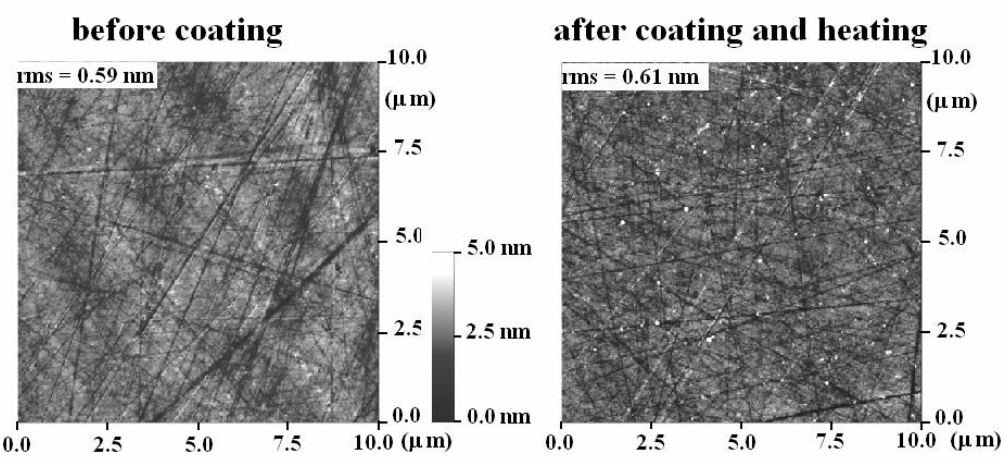


Figure 4: AFM high-spatial frequency roughness measured on mirror surface before and after coating, typical value of 0.6 nm rms.

6. MULTILAYER COATING AND REFLECTIVITY MAPPING

The mirror substrate was coated with a high-temperature multilayer. Studies of the thermal stability of a number of different high-temperature multilayer coatings on Si wafer test samples revealed that interface-engineered coatings provide high EUV reflectivity and sufficient long-term stability at elevated temperatures up to at least 500 °C [6]. The mirror substrate was coated with a candidate Mo/Si multilayer coating. A lateral gradient was applied to the layer period to keep the peak reflectivity at constant wavelength for varying incidence angle. A protective capping layer was also added to the MLM. After coating, the mirror was annealed at a temperature of 400 °C. A Si witness plate was mounted inside of the central mirror aperture during the coating and annealing process. The reflectance of the collector mirror was then measured for four series of equidistant measurement points along each quadrant boundary at the respective incidence angle for each location using a reflectometer and synchrotron radiation [7]. Figure 5 shows these four sets of reflectance data as a function of mirror radius. Generally, the peak reflectivity values reach 41% within the clear optical aperture of the collector. On the other hand, the witness sample, a super-polished Si wafer, exhibited a normal-incidence reflectance of more than 54 %. Consequently, it is concluded that the residual substrate surface roughness and other substrate-related properties are the primary and most likely cause of the reflectivity reduction observed for the mirror shell compared to the witness plate.

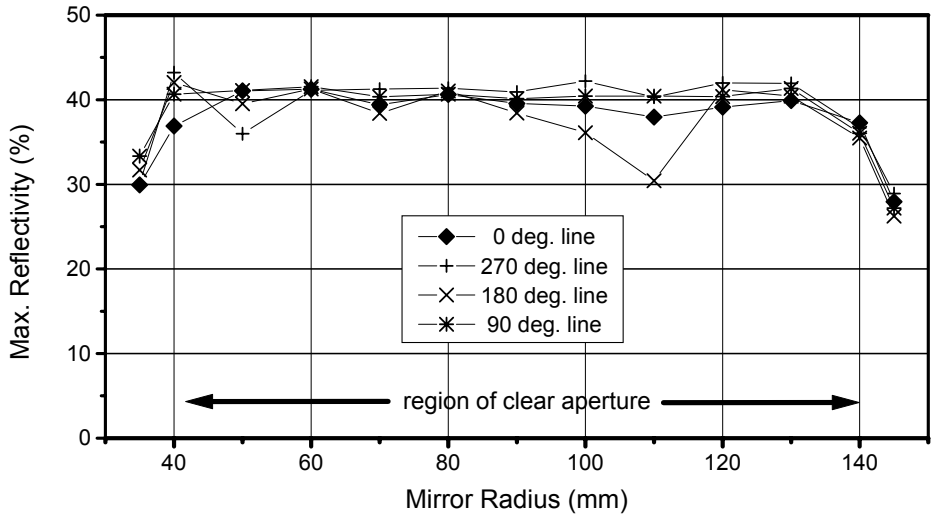


Figure 5: Measured maximum mirror reflectivity as a function of mirror radius for the four quadrant boundaries. Also indicated is the region of the clear optical aperture.

7. COLLECTOR PROTECTION AND LIFETIME TESTS

Apart from synchrotron radiation sources almost all other EUV sources produce some kind of debris. LPP sources generally produce particle and ion debris [5]. Suitable protection techniques are therefore needed to achieve the required collector lifetime performance and keep particle deposition and mirror erosion within acceptable limits. Previously, we have discussed the results of our studies of different protection strategies for the collector optics. Several debris mitigation methods were tested using ion time-of-flight measurements and secondary ion mass spectroscopy (SIMS) for analysis [8].

We have continued these studies by carrying out a series of lifetime tests prior to the installation of the collector mirror. Multilayer-coated Si witness samples were mounted at a distance from the LPP corresponding to the location of the collector surface. Some of the samples were coated with only eight layer periods of the high-temperature MLM coating and the capping layer to facilitate layer counting. Using just one debris mitigation technique the samples were exposed to 45 million pulses of a tin LPP. A comparison of the EUV reflectance measured with synchrotron radiation for a reference sample and for the exposed sample indicated that no reduction in reflectivity took place. Data obtained with SIMS analysis are shown in figure 6. In contrast to the more complex evolution of the relative height of the sputter peaks, the sputter depth can be readily used for quantitative analysis if the layer number is not too high. The data demonstrate that after 45 million pulses only one SIMS peak is missing and at least 7 periods of the multilayer are still remaining on the sample. Using this result as a basis for the layer erosion estimates and carrying out some multilayer reflectivity calculations, we conclude that the expected mirror lifetime (corresponding to a reflectivity drop by 10 %) is in excess of 2 billion pulses. When combining the employed debris mitigation technique with an additional mitigation method or with sacrificial MLM layers a lifetime on the order of at least 45 billion pulses is projected.

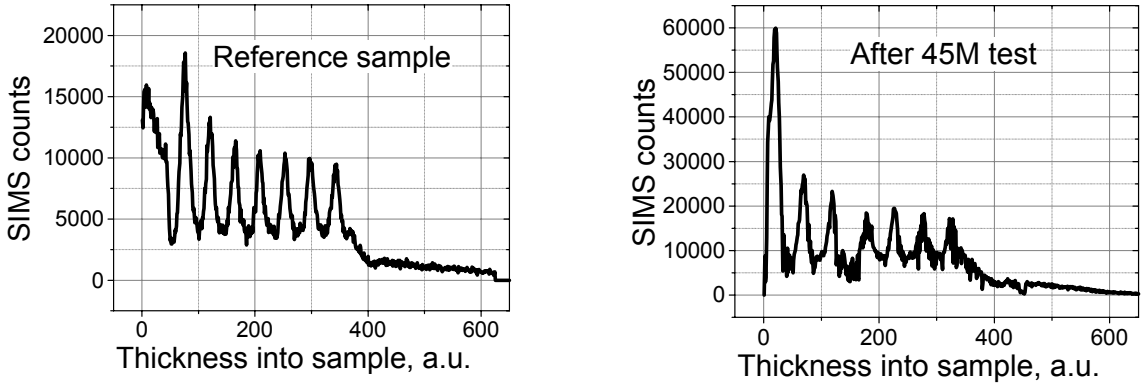


Figure 6: SIMS measurement result for sputtering multilayer material, counts as function of sputter depth. The reference sample shows 8 sputter peaks whereas the exposed sample shows 7.

8. SYSTEM PERFORMANCE TESTS AND MEASUREMENTS

8.1 Thermal Test Results

Several validation tests of the thermal properties of the substrate were carried out in a specially designed ultrahigh vacuum test chamber. Using various thermal sensors the heating ramp and level for both heat exchanger and collector shell were monitored in detail. Further testing, in particular of the uniformity of the heating, was implemented by imaging with an infrared camera through an on-axis inspection port at the chamber. A typical infrared image of the collector surface recorded for a target temperature of 300 °C is shown in figure 7. The value for the region labeled **1** indicates the average temperature for a selected segment on the mirror surface while the cross labeled **2** gives the temperature at a particular location point on the optical surface. The temperature readings were calibrated taking into account the corresponding emissivities of the substrate and mounting frame. A stable face temperature to with ± 5 °C could be maintained for long-term operation. Infrared imaging of the mirror surface was also carried out after the assembled collector was mounted in the source chamber.

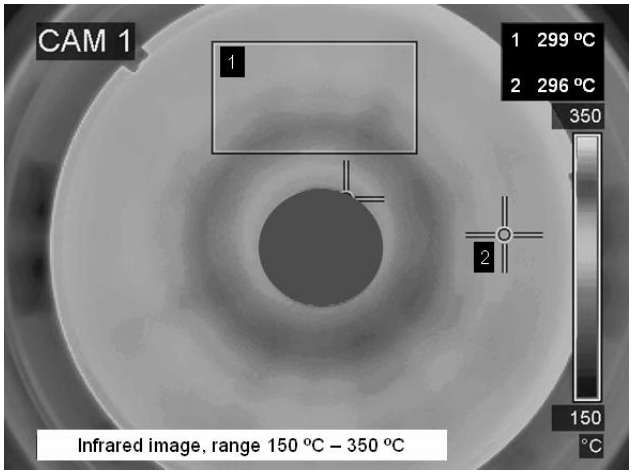


Figure 7: Infrared image of the substrate surface for a target temperature of 300 °C. The grey scale of the temperature range covers 150 °C - 350°C. Region **1** has an average temperature of 299 °C while point **2** is at 296 °C.

8.2 EUV Measurements at the Intermediate Focus

The mirror was mounted on its holder and the collector sub-assembly was then installed in the source chamber. Two overlapping semi-circular plates mounted on hinges were installed in front of the mirror surface for additional protection during measurements when it is not used. The plates can be opened under vacuum for exposure of the mirror. The alignment of the IF aperture with respect to the LPP focus point was carried out using visible light illumination. A calorimetric power meter was installed behind the IF aperture to detect the collected EUV radiation. The total EUV output power measured was 0.5 W when the LPP was operated with Sn droplet targets [2]. By insertion of a CaF_2 plate in front of the detector, the out-of-band contributions for the wavelength region above 130 nm was determined to be less than 15 % of the total signal detected with the power meter.

In order to monitor the entire EUV radiation distribution a Ce:YAG fluorescence converter plate with front-side Zr/Si coating was mounted at a distance of 150 mm behind the IF aperture. The wavelength-converted image transmitted through a vacuum window was recorded with a CCD camera. Figure 8 shows the result obtained when averaging only a few laser pulses illustrating the degree of illumination uniformity achieved. The slight decrease of the light intensity with radius was qualitatively reproduced by optical modeling. The obscurations seen in figure 8 are caused by the droplet generator and the laser beam stop. The dark area below the center obscuration is attributed to damage on the fluorescence converter. A few small circular regions on the mirror exhibiting low EUV reflectivity can also be discerned. The fluorescence converter proved to be a valuable tool for alignment optimization using video imaging.

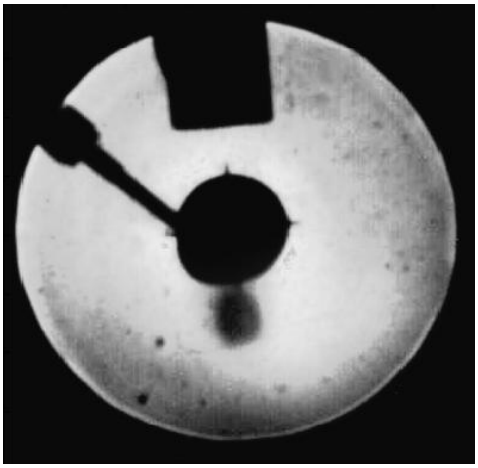


Figure 8: Fluorescence converter image of the collected EUV radiation observed behind the IF illustrating the illumination distribution. The obscurations are due to hardware related to beam stop and droplet generator.

9. SUMMARY AND CONCLUSIONS

We have described our progress in integrating a 320 mm diameter collector mirror into a LPP source chamber to collect the generated EUV radiation behind the IF. A heatable sub-aperture-size mirror was implemented. All manufacturing processes have been demonstrated to be compatible with the production of a 600 mm diameter collector. Thermal testing has yielded uniform heating of the mirror surface. At present, the collection efficiency is limited by reduced collector reflectivity caused mainly by the high-spatial frequency roughness of the mirror surface. However, with improved surface conditions average reflectivities of ~ 50 % can be reached with the high-temperature MLM coating employed here. The lifetime of the MLM coating has been shown to be sufficient for initial introduction into volume usage. With the mirror installed we have obtained first EUV measurements behind the IF.

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